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### Citation for published version:

Raffray, C & Pickering, MJ 2010, 'How Do People Construct Logical Form During Language Comprehension?', *Psychological Science*, vol. 21, no. 8, pp. 1090-1097.  
<https://doi.org/10.1177/0956797610375446>

### Digital Object Identifier (DOI):

[10.1177/0956797610375446](https://doi.org/10.1177/0956797610375446)

### Link:

[Link to publication record in Edinburgh Research Explorer](#)

### Document Version:

Publisher's PDF, also known as Version of record

### Published In:

Psychological Science

### Publisher Rights Statement:

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# How Do People Construct Logical Form During Language Comprehension?

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## Abstract

How do people interpret ambiguous sentences containing more than one quantifier, such as *Every kid climbed a tree*? We report four sentence-picture matching experiments that used priming to investigate whether comprehenders construct logical-form representations during processing. Experiment 1 investigated priming in active-voice sentences containing transitive verbs and found priming effects of quantifier-scope relations. Experiment 2 demonstrated priming effects when prime sentences were in the passive voice (e.g., *A tree was climbed by every kid*) and target sentences were in the active voice. Experiment 3 used prime sentences containing existentially quantified agents and universally quantified patients (e.g., *A kid climbed every tree*) and found no priming effects. Experiment 4 showed no priming effects when prime sentences contained plural nouns but no quantifiers (e.g., *Kids like to climb trees*), thus calling into question a visual-priming account of our priming effects. Our findings suggest that people construct logical-form representations, and they do so after constructing meaning-based representations involving quantifiers and thematic-role information.

## Keywords

quantifier scope, priming, logical form, thematic roles, comprehension

Received 5/18/09; Revision accepted 11/14/09

Speakers often wish to refer to different numbers of entities. To do this, they can use quantifiers such as *every* or *a*. Using quantifiers appears to be straightforward, yet it can lead to ambiguity when more than one quantifier is used. For example, the apparently simple sentence *Every kid climbed a tree* is not ambiguous with respect to the relationship between the verb and its arguments; it is clear that *every kid* is the subject of *climbed* and that *a tree* is the object of *climbed*. But the sentence is ambiguous in a different way. It may be that there is one tree, which every kid climbed; alternatively, every kid may have climbed a different tree. Linguists and philosophers have long assumed that the apparently simple form of sentences such as these hides ambiguity, and they have attempted to bring such ambiguity into the open using appropriate representations. But do people construct such representations when processing language, and, if so, what is the nature of these representations?

Interest in these representations goes back to Russell (1919), who used them to provide a precise account of when sentences were true or false. The analysis of such sentences has been central to the branch of linguistics known as formal semantics (which is concerned with the meaning of complex expressions and not merely individual words), most notably Montague Grammar (Dowty, Wall, & Peters, 1981). More recently, linguists have integrated formal semantics with

syntactic theory (e.g., May, 1985). All these approaches use a disambiguated logical form (LF) to describe sentences. In our example (ignoring tense), the interpretation in which every kid climbed a potentially different tree can be represented as (1a), and the interpretation in which there is one tree that every kid climbed can be represented as (1b):


$$\forall x [\text{Kid}(x) \rightarrow \exists y [\text{Tree}(y) \wedge \text{Climb}(x, y)]] \quad (1a)$$

$$\exists y [\text{Tree}(y) \wedge \forall x [\text{Kid}(x) \rightarrow \text{Climb}(x, y)]] \quad (1b)$$

The meaning of (1a) is “For every  $x$ , if  $x$  is a kid then there is some  $y$  such that  $y$  is a tree, and  $x$  climbed  $y$ .” The *universal* quantifier  $\forall$  takes scope over the expression within both sets of square brackets, and we refer to (1a) as the *universal-wide* interpretation. The meaning of (1b) is “For some  $y$ ,  $y$  is a tree and for every  $x$ , if  $x$  is a kid then  $x$  climbed  $y$ .” The *existential* quantifier  $\exists$  takes scope over the expression within both sets of square brackets, and we refer to (1b) as the *existential-wide* interpretation. In (1a), the universal quantifier takes wide scope; in (1b), the existential quantifier takes wide scope.

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Psychological Science  
 21(8) 1090–1097  
 © The Author(s) 2010  
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 sagepub.com/journalsPermissions.nav  
 DOI: 10.1177/0956797610375446  
 http://pss.sagepub.com  


Most linguists regard LF as a separate level of representation that sits between syntactic representation (e.g., constituent structures) and semantic interpretation (meaning). May (1985), for example, argued that LF involves so-called quantifier raising (see also Aoun & Li, 1993). In our example, *a tree* moves from after *climbed* to one of two “landing sites”: after *every kid* in the universal-wide interpretation (1a) and before *every kid* in the existential-wide interpretation (1b). In this way, the quantifiers (e.g.,  $\forall x$ ) achieve scope over their quantified elements (e.g., *Kid (x)*), just as one constituent can take scope over another constituent (i.e., c-command it) in a constituent-structure tree (Chomsky, 1981).

Psychologists have extensively investigated the mental representation and processing of syntactic information, both in comprehension (e.g., Frazier, 1987) and in production (e.g., Bock, 1986). But there has been little attempt to determine whether people construct LF representations and, if people do, what characteristics these representations have. The few studies concerned with the processing of quantifier-scope phenomena have focused on why people prefer particular interpretations of ambiguous sentences (Filik, Paterson, & Liversedge, 2004; Kurtzman & MacDonald, 1993; Paterson, Filik, & Liversedge, 2008). For example, Kurtzman and MacDonald asked people to judge the acceptability of passages containing ambiguous sentences, and they found a preference for the universal-wide interpretation of active-voice sentences (e.g., 1a for *Every kid climbed a tree*), but no preference for either interpretation of passive-voice sentences. These studies show that semantic interpretation is affected by quantifiers, but do not show whether people compute LF representations independently of semantic interpretation, or whether such representations intervene between syntactic and semantic representations, as would be compatible with May’s (1985) theory.

We therefore investigated whether it is possible to prime the abstract structure of LF representations during comprehension. Structural priming studies suggest that people compute linguistic representations during production (Bock, 1986) and comprehension (Branigan, Pickering, & McLean, 2005; Carey, Mehler, & Bever, 1970). Although most of these studies provide evidence for representations associated with syntax, other studies have shown priming of semantic representations in production (Bock, Loebell, & Morey, 1992; Chang, Bock, & Goldberg, 2003) and comprehension (Raffray, Pickering, & Branigan, 2007). If people compute an LF representation, it is therefore likely that it will be susceptible to priming (see Pickering & Ferreira, 2008).

We conducted four experiments using sentence-picture matching (Branigan et al., 2005; Raffray et al., 2007). In Experiment 1, the prime sentences were in the active voice and were similar to the target sentences (e.g., *Every kid climbed a tree*); hence, primes and targets had the same ambiguity. We predicted that participants would interpret target sentences in the same way that they interpreted prime sentences. In Experiment 2, the prime sentences were in the passive voice (e.g., *A tree was climbed by every kid*); these sentences were also

ambiguous regarding the two interpretations. Experiment 3 used active-voice prime sentences in which the order of the quantifiers was the reverse of their order in Experiment 1 (e.g., *A kid climbed every tree*); these sentences also had two interpretations. In Experiment 4, prime sentences were not ambiguous (e.g., *Kids like to climb trees*).

## Experiment 1

### Method

**Participants.** Thirty-two native English-speaking students from the University of Edinburgh were paid to participate.

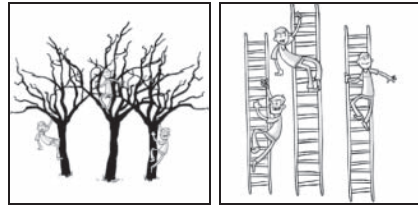
**Stimuli and procedure.** We constructed 24 sets of items (see Prime and Target Sentences Used in the Experiments in the Supplemental Material available online), each of which consisted of a prime sentence and a target sentence, two pairs of prime pictures, and a pair of target pictures. Prime and target sentences were of the form *Every noun verbed a noun*, with the two sentences using the same verb but different nouns (as verb repetition tends to enhance structural priming effects; see Pickering & Ferreira, 2008). In the universal-wide condition, a prime sentence such as *Every kid climbed a tree* was associated with the pictures at the top left of Figure 1a. In the existential-wide condition, the same sentence was associated with the pictures at the top right of Figure 1a. In both cases, the matching picture represented the appropriate interpretation of the prime sentence, and the nonmatching picture involved either a different agent (for half the items) or a different patient (for the other half; an example of the latter is shown in Fig. 1a). A target sentence such as *Every hiker climbed a hill* was presented along with two pictures (such as those in Fig. 1b); these pictures corresponded to the universal-wide and existential-wide interpretations of the sentence.

The items involved 12 verbs. All agent nouns were animate (e.g., *kid*, *hiker*); half of the object nouns were animate (e.g., *surfer*, *professor*), and half were inanimate (e.g., *ship*, *sculpture*). The animacy of patient nouns was kept constant between prime and target sentences, although the nouns themselves varied. The representation of agent and patient entities in all the matching and nonmatching pictures was as follows: Eight items were illustrated by three agent entities and either one or three patient entities (depending on interpretation), eight items were illustrated by four agent entities and either one or four patient entities, and eight items were illustrated by five agent entities and either one or five patient entities. The order of the pictures was counterbalanced across items and across prime- and target-sentence pairs.

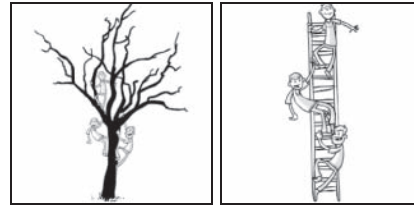
In addition, we constructed 72 unambiguous filler sentences and corresponding pairs of matching and nonmatching pictures. Forty-eight filler sentences used transitive verbs, and 24 filler sentences used intransitive verbs. Again, the agent nouns were animate, and the patient nouns were equally split between animate and inanimate. The nonmatching picture had

## a Prime Sentences and Pictures

### Universal-Wide Condition



### Existential-Wide Condition

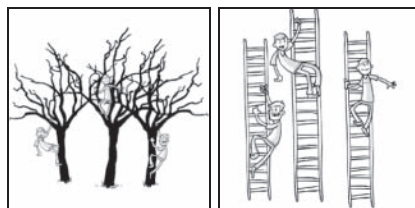


Experiment 1: *Every kid climbed a tree*

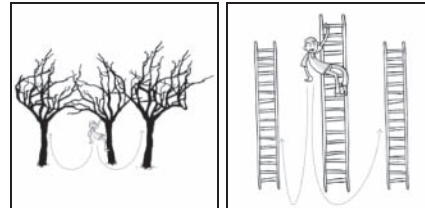
Experiment 2: *A tree was climbed by every kid*

Experiment 4: *Kids like to climb trees*

### Universal-Wide Condition



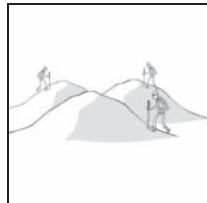
### Existential-Wide Condition



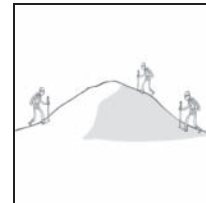
Experiment 3: *A kid climbed every tree*

## b Target Sentence and Pictures

### Universal-Wide Response



### Existential-Wide Response



*Every hiker climbed a hill*

**Fig. 1.** Sample sentences and corresponding pictures in the two conditions of each experiment. Participants were presented with a prime sentence and instructed to select the picture that matched their interpretation of the sentence (a). To observe the effects of priming, we then presented participants with a target sentence and gave them the same instruction (b). Sentence-picture matching was completed for a universal-wide condition and an existential-wide condition.

a different agent than did the matching picture for half of the filler sentences, and it had a different patient noun for the other half.

We constructed two lists containing all 24 items and all 72 fillers. Each list had 12 items per condition and one version of each item. Each list was randomized for each participant with the constraint that two, three, or four fillers intervened between items. Prime sentences and prime pictures immediately preceded target sentences and target pictures.

The stimuli were presented on a computer screen using E-Prime software (Psychology Software Tools, Inc., Pittsburgh, PA). Participants read a sentence and then used a button box to select the picture that best matched the sentence. Participants read a prime sentence and then selected between a picture that matched one interpretation of the prime sentence and a picture that did not match any interpretation of that sentence. They then read an ambiguous target sentence (e.g., *Every hiker climbed a hill*) and selected between a picture that matched the

universal-wide interpretation of that sentence and a picture that matched the existential-wide interpretation of that sentence. Seven practice trials preceded the experiment. The session lasted about 15 min.

**Coding and analysis.** One item was eliminated from this experiment (and also from Experiments 2–4) because of a programming error. We also eliminated trials on which a participant selected the incorrect prime picture. The remaining responses were coded according to whether the corresponding target selected was a universal-wide or an existential-wide picture.

We analyzed our data by modeling response-type likelihood using logit mixed-effect models (Jaeger, 2008). We started all analyses with a null model that included our binomial dependent variable and participants and items as random factors; we added the predictor variable or variables to this model (incrementally, if there was more than one predictor) to see whether the model was improved. Model fit was assessed using chi-square tests on the log-likelihood values to compare different models. All analyses were carried out in the R programming language and environment (R Development Core Team, 2008) using the lme4 software package (Bates, Maechler, & Dai, 2008).

## Results and discussion

Table 1 summarizes participants' selections, and Table 2 presents the results of the statistical analyses. Participants selected universal-wide target pictures significantly more often after selecting universal-wide prime pictures than after selecting existential-wide prime pictures (8%). Thus, participants appeared to construct an abstract representation incorporating quantifier-scope information, and this representation perseverated in a way that affected participants' choice of target

responses. The effect of priming between sentences with different interpretations suggests that participants computed an LF representation that was independent of sentence meaning.

## Experiment 2

What linguistic information is used to construct LF representations? When comprehenders adopted the universal-wide interpretation, they gave wide scope to the noun phrase at the start of the sentence. In doing this, they may have assigned wide scope to the first constituent of the sentence, wide scope to the subject, or wide scope to the agent, and then perseverated in this assignment. Discriminating among these possibilities would indicate whether a linear representation, grammatical representation, or thematic representation involving meaning is constructed before LF during language comprehension. The linear representation appears compatible with the findings of Kurtzman and MacDonald (1993); their results suggest that comprehenders' preferences make reference to linear order (e.g., the first quantified expression takes wide scope). The mapping of a grammatical relation to LF appears compatible with linguistic accounts (e.g., May, 1985), because it assumes that LF intervenes between a syntactic representation and meaning.

In Experiment 2, we attempted to distinguish among these accounts by using passive-voice prime sentences such as *A tree was climbed by every kid* and active-voice target sentences such as *Every hiker climbed a hill*. We hypothesized that if comprehenders assigned wide scope, for example, to the first quantified expression in the prime sentence (*a tree*), they should tend to assign wide scope to the first quantified expression in the target sentence (*every hiker*). Similarly, if they assign wide scope to the subject of the prime sentence (*a tree*), they should tend to assign wide scope to the subject of the target sentence (*every hiker*). In both of these cases, participants should be more likely to assign the universal-wide interpretation to the target sentence in the existential-wide condition than in the universal-wide condition. But if they assign wide scope to the agent of the prime sentence (*every kid*), they should tend to assign wide scope to the agent of the target sentence (*every hiker*). They should then be more likely to assign the universal-wide interpretation to the target sentence in the universal-wide condition than in the existential-wide condition.

## Method

Thirty-two different participants from the same population as in Experiment 1 were paid to participate. All experimental and filler pictures and target sentences were the same as in Experiment 1. Prime sentences used in Experiment 1 were rewritten in the passive voice for Experiment 2 (e.g., *A tree was climbed by every kid*). Half of the filler sentences were written in the passive voice. The procedure, coding, and analysis were the same as in Experiment 1.

**Table 1.** Frequency of Universal-Wide and Existential-Wide Responses by Condition in Experiments 1 Through 4

Experiment and prime type	Target selected	
	Universal-wide	Existential-wide
Experiment 1		
Universal-wide	262 (77%)	79 (23%)
Existential-wide	244 (69%)	109 (31%)
Experiment 2		
Universal-wide	262 (74%)	91 (26%)
Existential-wide	238 (67%)	116 (33%)
Experiment 3		
Universal-wide	525 (74%)	180 (26%)
Existential-wide	536 (76%)	168 (24%)
Experiment 4		
Universal-wide	589 (84%)	112 (16%)
Existential-wide	588 (85%)	106 (15%)



**Table 2.** Logit Mixed-Model Analyses for Experiments 1 Through 4

Predictor	Coefficient	SE	Wald Z	p
Experiment 1: best-fitting model included prime type, $\chi^2(1, N = 694) = 10.77, p < .001$ , log-likelihood = -312.9				
Intercept	1.44	0.420	3.42	< .001
Prime type = universal-wide	0.72	0.214	3.34	< .001
Experiment 2: best-fitting model included prime type, $\chi^2(1, N = 707) = 5.04, p < .05$ , log-likelihood = -384.9				
Intercept	0.91	0.254	3.57	< .001
Prime type = universal-wide	0.42	0.183	2.30	< .05
Experiments 1 and 2: best-fitting model included prime type, $\chi^2(1, N = 1,401) = 11.7, p < .001$ , log-likelihood = -749.1				
Intercept	0.97	0.228	4.25	< .001
Prime type = universal-wide	0.45	0.130	3.46	< .001
Experiment 3: no improvement on null model				
Experiments 1–2 vs. 3: best-fitting model included interaction between prime type and experiment, $\chi^2(1, N = 2,810) = 8.07, p < .01$ , log-likelihood = -1,452				
Intercept	0.95	0.211	4.51	< .001
Prime type = universal-wide	0.44	0.129	3.40	< .001
Experiment = Experiment 3	0.51	0.144	3.54	< .001
Interaction = universal-wide & Experiment 3	-0.54	0.188	-2.87	< .01
Experiment 4: no improvement on null model				
Experiments 1–2 vs. 4: best-fitting model included interaction between prime type and experiment, $\chi^2(1, N = 2,796) = 6.14, p < .05$ , log-likelihood = -1,301.3				
Intercept	1.11	0.211	5.27	< .001
Prime type = universal-wide	0.44	0.129	3.40	< .001
Experiment = Experiment 4	1.03	0.157	6.54	< .001
Interaction = universal-wide & Experiment 4	-0.51	0.205	-2.50	< .05

## Results and discussion

Table 1 summarizes participants' selections, and Table 2 presents the results of the statistical analyses. Participants selected universal-wide target pictures significantly more often after selecting universal-wide prime pictures than after selecting existential-wide prime pictures (7%). These results support the thematic account, rather than the grammatical account or the linear account, and they suggest that comprehenders map a representation containing thematic information to LF. We also conducted a combined analysis of Experiments 1 and 2 to determine whether quantifier-scope priming differed between active-voice and passive-voice prime sentences (see Table 2). Although there was significant priming across both experiments, priming did not differ between experiments. Thus, priming was unaffected by the relationship between grammatical relations and scope, or between word order and scope.

## Experiment 3

The results of Experiment 2 may suggest that comprehenders have a simple tendency to repeat the scope assignment to particular thematic roles (the *simple thematic-role account*). For example, comprehenders may be more likely to assign wide

scope to an agent if they have just assigned wide scope to another agent than if they have not. But in Experiment 2, the thematic roles were always quantified in the same way. In other words, agents were universally quantified, and patients were existentially quantified. Thus, it may be that comprehenders tended to repeat scope assignment to quantified thematic roles (the *quantified thematic-role account*). For example, comprehenders were more likely to assign wide scope to a universally quantified agent if they had just assigned wide scope to another universally quantified agent than if they had not. But it is also possible that Experiment 2 (and indeed Experiment 1) showed priming of which quantified expression took wide scope, without reference to any other aspect of the representation. Thus priming may simply have depended on the order of quantifiers (the *quantifier-order account*), with comprehenders being more likely to adopt a universal-wide interpretation for a sentence if they had just adopted a universal-wide interpretation for another sentence than if they had not.

Experiment 3 was designed to distinguish among these possibilities. We used prime sentences such as *A kid climbed every tree*, with existentially quantified agents and universally quantified patients. Our target sentences were the same as in Experiments 1 and 2, with universally quantified agents and existentially quantified patients. The simple thematic-role

account predicts that participants should be more likely to select universal-wide target pictures after selecting existential-wide prime pictures than after selecting universal-wide prime pictures. The quantified thematic-role account predicts that participants should be equally likely to select universal-wide target pictures after selecting existential-wide prime pictures or universal-wide prime pictures. The quantifier-order account predicts that participants should be more likely to select universal-wide target pictures after selecting universal-wide prime pictures than after selecting existential-wide prime pictures.

## Method

Sixty-four different participants from the same population as in the previous experiments were paid to participate. The prime sentences were the same as the sentences in Experiment 1, except that the quantifiers were switched. In the universal-wide condition, each prime sentence was associated with the same pictures as in Experiment 1. In the existential-wide condition, each prime sentence was associated with new pictures containing a single patient and three, four, or five agents (see Fig. 1). Filler and target sentences and pictures were the same as in Experiment 1, as were the procedure, coding, and analysis.

## Results and discussion

Table 1 summarizes participants' selections. Results showed no evidence that participants' choice of target picture was affected by the form of the prime sentence. To be confident that the manipulation in this experiment prevented priming, we compared Experiments 1 and 2 (64 participants), on the one hand, with Experiment 3 (64 participants), on the other hand (see Table 2). Priming was greater in Experiments 1 and 2 (7%) than in Experiment 3 (–2%); this result confirmed that the priming effects in Experiments 1 and 2 were due to prime and target sentences containing expressions with the same thematic role and quantifier. These results are therefore incompatible with the simple thematic-role account and with the quantifier-order account. Instead, they suggest that comprehenders tended to repeat scope assignment to quantified thematic roles. (The effect of experiment reported in Table 2 presumably occurred because priming in Experiments 1 and 2 occurred for the less-favored existential-wide interpretation.)

Another possible concern with Experiments 1 and 2 is that participants might simply have tended to choose visually similar pictures—for example, a target picture with a single patient (e.g., one hill) following a prime picture with a single patient (e.g., one tree). If so, the effects we observed would not be a result of the priming of quantifier-scope relations during sentence comprehension. This explanation is rendered less likely by the results of Experiment 3, in which no priming occurred even though the matching prime picture in the universal-wide condition was the same as the universal-wide target picture. But to be more confident that this picture-priming explanation was not correct, we conducted Experiment 4, in which prime

and target pictures were the same in both conditions, but the prime sentences were devoid of quantifiers.

## Experiment 4

### Method

Experiment 4 involved 64 different participants and used prime sentences containing bare plural noun phrases with generic interpretations. To bring about the generic interpretation, we constructed half of the prime sentences so that they involved additional verbs (e.g., *like* in *Kids like to climb trees*), and half so that they involved adverbs (e.g., *often* in *Sailors often spot airplanes*). All experimental and filler pictures and target sentences were the same as in Experiment 1, as were the procedure, coding, and analysis.

## Results and discussion

Table 1 summarizes participants' selections. Priming did not occur when the prime sentences were devoid of quantifiers. Thus, the priming effects in Experiments 1 and 2 were due to comprehension of doubly quantified sentences and not to visual similarity between prime and target pictures. To be more certain that the prime sentences caused the priming in Experiments 1 and 2, we compared Experiments 1 and 2 (64 participants), on the one hand, with Experiment 4 (64 participants), on the other hand (see Table 2). Priming was greater in Experiments 1 and 2 (7%) than in Experiment 4 (–1%); this result confirmed that the quantified sentences in Experiments 1 and 2 led to priming that did not occur with the generic sentences in Experiment 4.

Participants were more likely to select a universal-wide target picture following a generic prime sentence (84%; Experiment 4) than following a quantified prime sentence (72%; mean of Experiments 1 and 2). A likely explanation is that participants tended to interpret the generic sentences in Experiment 4 as having an LF similar to the LF of the universal-wide interpretations of the prime sentences in Experiments 1 and 2 (but that participants accepted that the existential-wide prime picture was compatible with these generic sentences). Supporting this explanation, an analysis that divided the experiment into fourths found fewer universal-wide interpretations of the target picture in the first fourth (78%) than in the other fourths (84%, 87%, and 86%). The generic prime sentences may therefore have led to long-term priming of the universal-wide interpretation of the target pictures. There were no similar trends in Experiments 1 through 3.

## General Discussion

The four experiments we conducted showed that participants tended to persevere in their interpretation of doubly quantified sentences. In all experiments, participants had to choose whether sentences such as *Every hiker climbed a hill* should be

assigned a universal-wide interpretation (in which the hikers climbed potentially different hills) or an existential-wide interpretation (in which the hikers climbed the same hill). Experiment 1 found that participants' choice was affected by their interpretation of active-voice prime sentences, such as *Every kid climbed a tree*. Experiment 2 used passive-voice prime sentences, such as *A tree was climbed by every kid*, and found effects equivalent to those in Experiment 1. Experiment 3 used prime sentences, such as *A kid climbed every tree*, that contained existentially quantified agents and universally quantified patients, and found no priming. Experiment 4 used generic prime sentences, such as *Kids like to climb trees*, and did not find priming, thereby ruling out a visual-priming explanation of the results.

Experiments 1 and 2 therefore provide evidence that comprehenders construct disambiguated abstract representations that specify quantifier-scope relations. Because prime and target sentences referred to different entities in these experiments, comprehenders must have computed a representation that was independent of the final meaning of the sentence, as might be captured by a situation model (e.g., Zwaan & Radvansky, 1998). Priming could not have been a result of repetition of the situation model described by the prime sentence because the prime and target sentences referred to different entities.

Another possibility is that comprehenders might have primed formal characteristics of a situation model (i.e., abstracting over the entities) so that different entities could be linked by analogy. Such an account would treat the situation model for the universal-wide interpretation of *A kid climbed every tree* (see the left-most prime picture for Experiment 3 in Fig. 1a) as equivalent to the situation model for the universal-wide interpretation of *Every kid climbed a tree* (see the left-hand target picture in Fig. 1b). However, no priming occurred between these interpretations in Experiment 3. Instead, the priming effects we observed appear to reflect the construction of an LF representation.

Taken together, Experiments 2 and 3 support the quantified thematic-role account, according to which comprehenders persevere in their assignment of scope to quantified thematic roles. Experiment 2 found priming and suggested that the assignment of scope did not adhere to grammatical relations (e.g., the subject takes wide scope) or linear order (e.g., the first quantified expression takes wide scope), but rather involved thematic roles. Experiment 3 did not find priming and therefore we ruled out an alternative explanation according to which priming was due to the preservation of quantifier order. At the same time, Experiment 3 demonstrated that thematic roles only affected scope relations in conjunction with quantifier repetition (e.g., a universally quantified agent takes wide scope). This suggests that LF is affected by aspects of meaning. How can LF be affected by meaning and yet independent of it?

We propose that people comprehend sentences by accessing the meanings of the words in a sentence and incrementally

building up a syntactic representation that determines which noun phrases serve as which arguments of the verb. In *Every hiker climbed a hill*, this representation would capture that *every hiker* is the subject of *climbed* and that *a hill* is the object of *climbed*. In addition, comprehenders determine that *a hiker* or *hikers* is the agent of *climbed* and that *a hill* or *hills* is the patient of *climbed*, and that *hiker* is universally quantified and that *hill* is existentially quantified. This means that comprehenders have determined the quantificational information that will allow them to compute scope relations (but have not fixed the number of hikers or hills). At this point, they know something about the meaning of the sentence but have not chosen a disambiguated interpretation. Then they can construct a disambiguated LF representation that has been informed by the aspects of meaning encoded in thematic roles.

Finally, comprehenders interpret the LF with respect to the world (which in our experiments corresponded to a picture). In other words, quantifier-scope relations are computed over an interpreted representation that includes thematic information (e.g., Parsons, 1991). However, the construction of LF may also proceed incrementally, as long as it lags behind assignment of thematic roles and quantifiers to arguments. For example, comprehenders may assign the agent role to *every hiker* after encountering *climbed*, then construct a partial LF representation that includes the universally quantified expression *every hiker*, then assign the patient role to *a hill*, and finally construct a complete LF representation.

This account does not fit with linguistic explanations in which LF sits between syntactic representation and final interpretation (e.g., May, 1985). However, this account is compatible with the intuition that it is possible to understand something about complex quantified sentences without resolving all the quantifiers—the comprehender assigns thematic roles but stops at this point. Our findings demonstrate that people construct LF representations during comprehension and that such representations, like representations of syntax, are able to persist and affect subsequent processing.

## Acknowledgments

The authors acknowledge Martin Corley and Janet McLean for statistical assistance.

## Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

## Funding

This work was funded by a grant from the Economic and Social Research Council (Grant RES-062-23-0376).

## Supplemental Material

Additional supporting information may be found at <http://pss.sagepub.com/content/by/supplemental-data>



## References

- Aoun, J., & Li, Y.A. (1993). *Syntax of scope*. Cambridge, MA: MIT Press.
- Bates, D., Maechler, M., & Dai, B. (2008). lme4: Linear mixed-effects models using S4 classes [Computer software]. Boston: Free Software Foundation. Retrieved April 30, 2010, from <http://lme4.r-forge.r-project.org>
- Bock, J.K. (1986). Syntactic persistence in language production. *Cognitive Psychology*, 18, 355–387.
- Bock, J.K., Loebell, H., & Morey, R. (1992). From conceptual roles to structural relations: Bridging the syntactic cleft. *Psychological Review*, 99, 150–171.
- Branigan, H.P., Pickering, M.J., & McLean, J.F. (2005). Priming prepositional-phrase attachment during comprehension. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 31, 468–481.
- Carey, P., Mehler, J., & Bever, T.G. (1970). Judging the veracity of an ambiguous sentence. *Journal of Verbal Learning and Verbal Behavior*, 9, 243–254.
- Chang, F., Bock, K., & Goldberg, A.E. (2003). Can thematic roles leave traces of their places? *Cognition*, 90, 29–49.
- Chomsky, N. (1981). *Lectures on government and binding*. Dordrecht, The Netherlands: Foris.
- Dowty, D.R., Wall, R.E., & Peters, S. (1981). *Introduction to Montague semantics*. Dordrecht, The Netherlands: Kluwer.
- Filik, R., Paterson, K.B., & Liversedge, S.P. (2004). Processing doubly-quantified sentences: Evidence from eye-movements. *Psychonomic Bulletin & Review*, 11, 953–959.
- Frazier, L. (1987). Sentence processing: A tutorial review. In M. Coltheart (Ed.), *Attention and performance XII: The psychology of reading* (pp. 559–586). Hillsdale, NJ: Erlbaum.
- Jaeger, T.F. (2008). Categorical data analysis: Away from ANOVAs (transformation or not) and towards logit mixed models. *Journal of Memory and Language*, 59, 434–446.
- Kurtzman, H.S., & MacDonald, M.C. (1993). Resolution of quantifier scope ambiguities. *Cognition*, 48, 243–279.
- May, R. (1985). *Logical form: Its structure and derivation*. Cambridge, MA: MIT Press.
- Parsons, T. (1991). *Events in the semantics of English*. Cambridge, MA: MIT Press.
- Paterson, K.B., Filik, R., & Liversedge, S.P. (2008). Competition during the processing of quantifier scope ambiguities: Evidence from eye movements during reading. *Quarterly Journal of Experimental Psychology*, 61, 459–473.
- Pickering, M.J., & Ferreira, V.S. (2008). Structural priming: A critical review. *Psychological Bulletin*, 134, 427–459.
- R Development Core Team. (2008). *R: A language and environment for statistical computing*. Retrieved April 30, 2010, from <http://www.R-project.org>
- Raffray, C.N., Pickering, M.J., & Branigan, H.P. (2007). Priming the interpretation of noun-noun combinations. *Journal of Memory and Language*, 57, 380–395.
- Russell, B. (1919). *Introduction to mathematical philosophy*. London: Allen & Unwin.
- Zwaan, R.A., & Radvansky, G.A. (1998). Situation models in language comprehension and memory. *Psychological Bulletin*, 123, 162–185.